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**Final Progress Report**  
**DAAH-04-96-1-0379**  
**Multi-User Detection for Next-Generation CDMA:Final Report**

**Final Progress Report**

- (1.) Statement of the problem studied**
- (2.) Summary of the most important results**
- (3.) Listing of all publications and technical reports**
- (4.) List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project**

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### **(1.) Statement of the problem studied**

The overall objective of this grant was to investigate basic research issues on signal processing for demodulation of multiuser digital wireless communication systems of interest to future U.S. Army terrestrial tactical needs. This study motivated by the emergence over the past years of the field of multiuser detection from previous ARO-sponsored projects led by the principal investigators.

A major goal of this project was to design and analyze detectors that could be used with long-sequence CDMA. This is the Direct-sequence method employed in several civilian and military spread spectrum systems. To that end, random spreading models are used to obtain succinct figures of merit based on congestion and bandwidth.

## **(2.) Summary of the most important results**

**i.** Fast adaptive algorithms for linear and nonlinear multiuser detection based on new scalable architectures.

**ii.** A new iterative algorithm whose parameters have been obtained analytically using the theory of asymptotic distribution of eigenvalues of random matrices.

**iii.** Using random matrix models, we have been able to obtain a general method to analyze the fundamental limits of multiuser detectors when used with error control codes and randomly spread CDMA. The designer of a CDMA system can use this method to obtain the optimum coding redundancy/ spreading gain tradeoff. show that the spectral efficiency of CDMA can be multiplied by a factor of roughly 4, by increasing receiver complexity and by increasing the number of users per chip from 1/4 (typical of current systems) to 2.

**iv.** A general formula which for an arbitrary fading distribution, number of users to spreading gain ratio, and signal-to-noise ratio quantifies the gain in spectral efficiency achievable by optimum nonlinear processing over optimum linear processing.

**v.** Transmitter Power control strategies that adjust transmitted power as a function of the individual slow-fading level in order to maximize spectral efficiency.

**vi.** In the case of Rayleigh fading, and for any energy per bit we have shown that optimum transmitted power control enables the spectral efficiency to be unbounded as the number of users and the receiver complexity increases.

**vii.** Analysis and design of multiuser detectors in eavesdropping environments where there are large power imbalances between desired and interfering users.

**(3.) Publications and technical reports supported under this grant or contract.**

**Book**

S. Verdú,  
Multiuser Detection, Cambridge University Press, New York: 1998.

**(a) Papers Published in Peer-Reviewed Journals**

D. Tse and S. Verdú, "Optimum Asymptotic Multiuser Efficiency of Randomly Spread CDMA," IEEE Trans. Information Theory, pp. 2718-2723, November 2000

S. Verdú, "Wireless Bandwidth in the Making," IEEE Communications Magazine, Invited Paper, Special Issue of High-Speed Wireless Access, vol. 38, no. 7, pp. 53-58, July 2000

S. Verdú and S. Shamai, "Spectral Efficiency of CDMA with Random Spreading," IEEE Trans. Information Theory, vol 45, no. 2, pp. 622-640, Mar. 1999.

A. McKellips and S. Verdú, "Eavesdropper Performance in cellular CDMA," European Transactions on Telecommunications, vol. 9, no. 4, pp. 379-390, July-Aug. 1998.

A. McKellips and S. Verdú, "Maximin Performance for Binary-Input Channels with Uncertain Noise Distributions," IEEE Trans. on Information Theory, vol. 44, no. 3, pp. 947-972, May 1998.

S. Shamai (Shitz), S. Verdú and R. Zamir, "Systematic Lossy Source-Channel Coding," IEEE Trans. on Information Theory, vol. 44, no. 2, pp. 564-579, March 1998.

N. Mandayam and S. Verdú, "Analysis of an Approximate Decorrelating Detector", Wireless Personal Communications, Special issue on "Interference in Mobile Wireless Systems" vol. 6, no. 1-2, pp. 97-111, January 1998.

H. Huang and S. Verdú, "Linear Differentially Coherent Multiuser Detection for Multipath Channels," Wireless Personal Communications, Special Issue on "Interference in Mobile Wireless Systems." vol. 6, no. 1-2, pp. 113-136, January 1998.

**(3.) continued**

A. McKellips and S. Verdú, "Worst-case Additive Noise for Binary-Input Channels under Constraints of Variance and Divergence," IEEE Trans. on Information Theory, vol. 43, no.4, pp. 1256-1264, July 1997.

**(b) Papers Published in Conference Proceedings**

R. Mueller and S. Verdú, "Spectral Efficiency of low-complexity multiuser detectors," IEEE International Symposium on Information Theory, Sorrento, Italy, June 27- July 1 2000

S. Shamai, B. Zaidel and S. Verdú, "On Information Theoretic Aspects of Intra and Inter Cell Interference Mitigation in Coded and Randomly Spread Signaling," Conference on Interference Rejection and Signal Separation, New Jersey Institute of Technology, Newark, NJ, March 14, 2000

S. Shamai (Shitz), S. Verdú, B. M. Zaidel, "Spectral Efficiency of Randomly Spread DS-CDMA in a Multi-Cell Model," Thirty-seventh Allerton Conf. on Communications, Control and Computing, Allerton House, Monticello, IL, Sep. 22-24, 1999.

N. Zhang, A. Poon, D. Tse, R. Brodersen and S. Verdú, "Trade-offs of Performance and Single-Chip Implementation of Indoor Wireless Multi-Access Receivers, 1999 IEEE Wireless Communications and Networking Conference, New Orleans, LA, Sep. 21-24, 1999.

S. Shamai (Shitz) and S. Verdú, "Capacity of CDMA Fading Channels," Proc. 1999 IEEE Workshop on Information Theory and Networking, Metsovo, Greece, June 1999.

D. Tse and S. Verdú, "Optimum Multiuser Asymptotic Efficiency of CDMA with Random Spreading," Proc. 1999 IEEE Information Theory Workshop on Detection, Estimation, Classification and Imaging, p. 28, Feb. 24-26, 1999, Santa Fe, NM.

S. Verdú and S. Shamai, "Capacity of CDMA with Random Spreading and Multiuser Detection," IEEE Fifth International Symposium on Spread Spectrum Techniques and Applications, pp. 155-159, Sun City, South Africa, Sept. 2-4, 1998.

**(3.) continued**

S. Verdú and S. Shamai, "Spectral Efficiency of Direct-Sequence Spread-Spectrum Multiaccess with Random Spreading," 1998 IEEE Information Theory Workshop, pp. 64-67, Killarney, Ireland, June 22-26, 1998.

S. Verdú and S. Shamai, "Information Theoretic Aspects of Coded random Direct-Sequence Spread-Spectrum," Proc. IEEE 9th Mediterranean Electrotechnical Conference (MELECON'98), pp. 1328-1332, Tel Aviv, Israel, 18-20 May, 1998.

A. McKellips and S. Verdú, "Eavesdropping Syndicates in cellular Communications," 48th IEEE Vehicular Technology Conference Record, Ottawa, Canada, Vol. 1, May 1998, pp.318-322.

S. Verdú, "Information Theory and Multiuser Detection," Sixth Symp. Interference Rejection and Signal Separation in Wireless Communications, New Jersey Inst. of Technology, Newark, NJ, March 17, 1998.

A. L. McKellips and S. Verdú, "Multiuser detection for eavesdropping in cellular CDMA" presented at the Thirty-first Annual Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, California, November 1997.

M. Honig, R. Ratasuk and S. Verdú, "Blind Adaptive Space-Time Linear Multiuser Detection," Proc. Thirty-fifth Annual Allerton Conference on Communications, Control and Computing, pp 83-92 Allerton House, Monticello, IL, Sep. 29-Oct 1, 1997.

S. Verdú and S. Shamai (Shitz), "Multiuser Detection with Random Spreading and Error-Correction Codes: Fundamental Limits," Proc. Thirty-fifth Annual Allerton Conference on Communications, Control and Computing, pp 470-482, Allerton House, Monticello, IL, Sep. 29- Oct 1, 1997.

S. Shamai, S. Verdú, and R. Zamir, " Information Theoretic Aspects of Systematic Coding", Proc. of the International Symposium on Turbo Codes and Related Topics, Brest, France, 3-5 Sep., 1997.

**(c) Papers presented at meetings but not published in conference proceedings**

S. Verdú, "Bandwidth vs. Power: Asymptotic Results," ForneyFest American Academy of Arts and Sciences, Cambridge, MA, March 3-4, 2000

S. Verdú, "Increasing Spectral Efficiency in Wireless," Invited Talk, Workshop on Digital Transceiver Design, New Jersey Center for Wireless Communications, Newark, NJ, October 5, 1999.

**(3.) continued**

S. Verdú, "Poisson Communication Theory, Invited Talk, The International Technion Communication Day in honor of Israel Bar-David, Haifa, Israel, March 25, 1999.

S. Verdú, "Multiuser Detection with Long Spreading Sequences," Invited Plenary Talk, Second Annual UCSD Conference on Wireless Communications, Feb. 28 - Mar. 2, 1999, San Diego, CA.

S. Verdú, "Multiuser Detection: Signal Processing for Multiaccess," NSF/ONR Workshop on Future Directions in Systems and Control Research in Communication Networks, Airlie House, VA, Nov. 6, 1998.

S. Verdú, "Channel Capacity: Open Problems," Information Theory: The first fifty years and beyond, Royal Academy of Sciences of the Netherlands, Amsterdam, June 17-19, 1998.

A. McKellips and S. Verdú, "Least Favorable Additive Noise under a Divergence Constraint," Proc. 1997 Int. Symposium on Information Theory, pp. 533, Ulm, Germany, July 1997.

A. McKellips and S. Verdú, "Least Favorable Additive Noise under a Divergence Constraint ", Proc. 1997 Int. Symposium on Information Theory, Ulm, Germany, July 1997

S. Verdú, "Demodulation in the Presence of Multiaccess Interference," ARO/ARL Federated Laboratory Workshop on Spread Spectrum for Tactical Mobile Wireless Communications, University of Maryland, College Park, MD, June 19, 1997.

**(d) Manuscripts submitted, not yet published**

S. Shamai and S. Verdú, "The Impact of Frequency-flat Fading on the Spectral Efficiency of CDMA," IEEE Trans. Information Theory, submitted.

R. Mueller and S. Verdú, "Low-complexity methods for interference mitigation in vector channels," IEEE J. Selected Areas in Communications, submitted.



#### **(4.) Participating Scientific Personnel**

##### **Principal Investigator:**

Sergio Verdú

##### **Postdoctoral Fellows:**

Ralf Mueller

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##### **Graduate Students:**

Andrew McKellips (PhD August 1999)

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